

THE STRUCTURE OF THE STRONGLY LENSED GAMMA-RAY SOURCE B2 0218+35

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ABSTRACT

Strong gravitational lensing is a powerful tool for resolving the high energy universe. We combine the temporal resolution of *Fermi*-LAT, the angular resolution of radio telescopes, and the independently and precisely known Hubble constant from the analysis by the Planck collaboration, to resolve the spatial origin of gamma-ray flares in the strongly lensed source B2 0218+35. The lensing model achieves 1 milliarcsecond spatial resolution of the source at gamma-ray energies. The data imply that the gamma-ray flaring sites are separate from the radio core: the bright gamma-ray flare (MJD: 56160 - 56280) occurred 51 ± 8 pc from the 15 GHz radio core, toward the central engine. This displacement is significant at the $\sim 3\sigma$ level, and is limited primarily by the precision of the Hubble constant. B2 0218+35 is the first source where the position of the gamma-ray emitting region relative to the radio core can be resolved. We discuss the potential of an ensemble of strongly lensed high energy sources for elucidating the physics of distant variable sources based on data from *Chandra* and SKA.

Subject headings: Gravitational lensing: strong – Gamma-rays: jets – Quasars: individual (B2 0218+35) – Cosmology: cosmological parameters

1. INTRODUCTION

The high-energy universe is dominated by extreme and violently variable objects. The powerful jets of relativistic plasma associated with these sources are the largest and the most efficient particle accelerators known. The energy source, the energy dissipation mechanism and the particle acceleration mechanism in these fast flares of non-thermal radiation remain puzzling. Proposed mechanisms include relativistic shocks and magnetic reconnection (Zenitani & Hoshino 2001; Stawarz & Ostrowski 2002; Lyutikov & Uzdensky 2003; Kirk & Skjæraasen 2003; Jaroschek et al. 2004; Lyubarsky 2005; Proga 2005; McKinney 2006; Zenitani & Hoshino 2007; Komissarov et al. 2007; Zweibel & Yamada 2009; Giannios et al. 2009; Tchekhovskoy et al. 2010; Nalewajko et al. 2011; Tchekhovskoy et al. 2011; Cerutti et al. 2012; Hoshino 2012; Sironi & Spitkovsky 2014; Guo et al. 2015; Guo et al. 2014; Nalewajko et al. 2015; Moscibrodzka et al. 2015; Broderick & Tchekhovskoy 2015; MacDonald et al. 2015; Tchekhovskoy & Bromberg 2015).

One of the limitations to understanding these sources is our inability to localize the spatial origin of the emission. This failure is a direct result of the poor resolution of gamma-ray telescopes that reach, at best, an angular resolution of 0.1 deg. This angular resolution is unlikely to improve substantially with future instruments because it is limited by fundamental physical effects including nuclear recoil.

Gravitational lensing magnifies distant sources. Thus lensed gamma-ray blazars offer the best opportunity for resolving the locations of the emitting regions. For example, the bright blazar PKS 1830-211 is a lensed system (Barnacka et al. 2011). Analysis of the time delays between gamma rays from the mirage images of the flaring

episodes, combined with the lens model for this source reveals that two gamma-ray flares originated from a region within 100 pc from the central engine. Two additional gamma-ray flares originated at least 1.5 kpc from the central engine (Barnacka et al. 2015a). The existence of multiple variable emitting regions along the jet pose challenges for understanding the particle acceleration mechanism.

A second gravitationally lensed blazar B2 0218+35 offers further opportunities to explore the origin of the variable gamma-ray emission. This well-observed system has a number of features that enable the derivation of strong constraints on the nature of the gamma-ray source. The lens galaxy, observed with HST, is surprisingly simple and isolated (Wucknitz et al. 2004). There are extensive high-resolution radio observations of the lensed radio jet at several wavelengths. The *Fermi*-LAT light curve includes two flares, one of long duration and one short flare.

Based on the optical observations of the lens system and the radio observations of the lensed source, we demonstrate that the positions of the radio core and jet can be localized to 1 milliarcsecond. Localization of the gamma-ray source relative to the radio emitting regions requires both the time resolution of the *Fermi*-LAT light curve and a well-measured Hubble constant (Barnacka et al. 2014a, 2015b).

The *Fermi*-LAT light curves provide time delays with an accuracy of a few hours. If the time delay originates from the resolved radio core, the associated Hubble constant should be the true value obtained with independent techniques. If there is an offset of even a few milliarcseconds between the gamma-ray emitting region and the radio core, the time delay will imply a Hubble constant that differs from the true value measured with many independent methods (Freedman et al. 2001;

Freedman & Madore 2010; Suyu et al. 2010; Riess et al. 2011a,b; Freedman et al. 2012; Chávez et al. 2012; Efstathiou 2014; Suyu et al. 2013). Evidently, if the Hubble constant is well-known, the offset between the gamma-ray emitting region and the radio core can be derived with remarkable significance limited only by the accuracy of the time delay and the independently determined Hubble constant (Barnacka et al. 2015b).

We introduce the optical and radio observations of the gravitationally lensed blazar B2 0218+35 and we reconstruct the properties of the lens and the source (Sections 2 and 3). In Section 4, we use the Fermi-LAT data to explore the gamma-ray properties of B2 0218+35. We focus on two gamma-ray flares where we measure gravitationally induced time delays (Section 5). In Section 6, we combine the measurements of the gamma-ray time delays, the well-resolved position of the radio core, the reconstructed gravitational potential of the lens, and we explore the relative spatial origin of the two gamma-ray flares. Finally, we apply the Hubble parameter tuning approach, where we use the independently measured Hubble constant to localize the gamma ray emission relative to the radio core. We compare the results for B2 0218+35 with those for PKS 1830-211. We discuss the implications of the source structure for gamma-ray emission mechanisms in Section 7. We also propose extension of this approach to sources that will be observed with SKA and *Chandra*. We conclude in Section 8.

2. B2 0218+35: A GRAVITATIONALLY-LENSED SYSTEM

B2 0218+35 is a gravitationally-lensed system with the smallest known Einstein radius (330 mas) (O’Dea et al. 1992; Patnaik et al. 1995). The system consists of a bright blazar at redshift $z_S = 0.944 \pm 0.002$ (Cohen et al. 2003), lensed by an apparently isolated spiral galaxy at redshift $z = 0.6847$ (Browne et al. 1993). The lens bends the emission of the jet into two bright images of the core and extended structures, including an Einstein ring (Patnaik et al. 1992; O’Dea et al. 1992; Patnaik et al. 1993, 1995; Jackson et al. 2000; Biggs et al. 2001, 2003).

The first measurement of the time delay using VLA 15 GHz polarization observations yielded a value of 12 ± 3 days (Corbett et al. 1996). Biggs et al. (1999) used the results of a three-month VLA monitoring campaign at two frequencies and obtained a time delay of 10.5 ± 0.4 days. Cohen et al. (2000) used high-precision VLA flux density measurements, over the same epoch as Biggs et al. (1999), and measured a time delay of $10.1^{+1.5}_{-1.6}$ days.

This system has been a “golden lens” for Hubble constant measurement (Wucknitz et al. 2004). However, despite precise measurements of the time delay, a clean lens environment without nearby companions or a surrounding cluster, and a negligible number of structures along the line of sight which would complicate the modeling of the lens, the H_0 values derived from this system are in the range $61\text{--}78 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (York et al. 2005; Lehár et al. 2000; Wucknitz et al. 2004). The most recent attempt to measure H_0 for B2 0218+35, using a time delay of 11.46 ± 0.16 days based on gamma-ray emission, results in a Hubble constant of $64 \pm 4 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (Cheung et al. 2014).

This large scatter in the H_0 values can indicate complex source structure (Barnacka et al. 2015b). To investigate

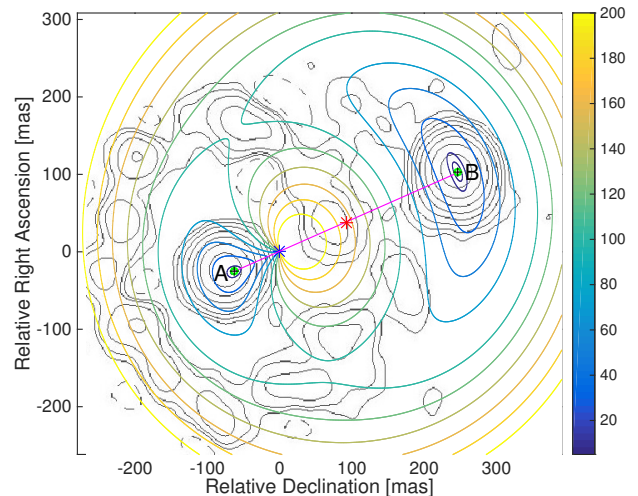


FIG. 1.— Image plane. The colored contours show the Fermat surface. The coordinates are relative to the reconstructed lens position. Black crosses show the reconstructed mirage image positions. Green open circles show the positions of the 15 GHz mirage images of B2 0218+35. The gray contours show the radio emission observed at 1.687 GHz. The magenta line indicates the axis connecting the mirage images. The blue star shows the final position of the lens center. The red star indicates the reconstructed position of the 15 GHz radio source.

the detailed source structure, we build a lens model.

3. B2 0218+35 AS A HIGH RESOLUTION COSMIC TELESCOPE

B2 0218+35 is a perfect system for lens modeling. The simplicity and isolation of the lensing galaxy results in a clean gravitational lens potential. Previous lens models show that the observations are consistent with a Singular Isothermal Sphere (SIS) model for the mass distribution of the lens (Wucknitz et al. 2004; Larchenkova et al. 2011). These studies focused on the properties of the lensing galaxy and measurement of the Hubble parameter (York et al. 2005). Here, we use the lens as a high-resolution telescope to investigate the structure of the source over wavelengths ranging from radio to gamma-ray energies. We first use the lens model to determine an accurate position for the radio core. We evaluate the uncertainties in the model using Monte Carlo simulations.

3.1. Constraining the Lens

We base the model on radio VLBA observations at 15 GHz, where the position of mirage images of the core are measured with 0.6 mas accuracy (1994 Oct 3, Patnaik et al. 1995). The position of the mirage image B (brighter image located outside the Einstein ring; green circle in Figure 1) with respect to image A (green circle, Figure 1), along with all the parameters, are summarized in Table 1.

The positions of the 15 GHz mirage images yield a measure of the Einstein radius and the position of the source. The Einstein radius of the lens, with a mass distribution close to a SIS, is half the distance between the mirage images; $\theta_E = (\theta_A + \theta_B)/2 = 167.2 \pm 0.6 \text{ mas}$. The corresponding lens mass within one Einstein radius is $\sim 2 \times 10^{10} M_\odot$. For a lens of such a small mass, resolution of the mirage images is possible only with high-resolution imaging.

TABLE 1
INPUT PARAMETERS FOR THE LENS MODELING

Parameter	Value
Image A at 15 GHz	(0,0)
Image B at 15 GHz	$(309.2, -127.4) \pm 0.6 \text{ mas}$ ^a
Estimated Source Position	$(154.6, -63.7) \pm 10 \text{ mas}$
Einstein Angle	$\theta_E = 167.2 \pm 0.6 \text{ mas}$
Approximate Lens Position	$(56, -23) \pm 20 \text{ mas}$
Optical Center of the Galaxy ^b	
– no masking	$(57 \pm 4, 1 \pm 6)$
– spiral arms masked	$(75 \pm 6, -6 \pm 13)$
Position Angle	$\phi_0 = 49^\circ$ ^c
Time Delay at 15 GHz	$10.1 \pm 1.6 \text{ days}$ ^d , $10.5 \pm 0.4 \text{ days}$ ^e
Magnification Ratio at 15 GHz	3.623 ± 0.065 ^f
Source Redshift	$z_S = 0.944$ ^g ,
Lens (Galaxy) Redshift	$z_L = 0.6847$ ^h

^aPatnaik et al. (1995)

^bYork et al. (2005)

^cYork et al. (2005)

^dCohen et al. (2000)

^eBiggs et al. (1999)

^fPatnaik et al. (1995)

^gCohen et al. (2003)

^hBrowne et al. (1993)

The mirage images appear on the axis defined by the position of the source and the lens (magenta line in Figure 1), at distances of $\pm\theta_E$ from the source. The source is located at half the distance between the mirage images, $\theta_S = (\theta_A - \theta_B)/2$. The source position may deviate from the axis if the mass distribution deviates from a SIS. In the model described below, we thus search for the best source position within 10 mas from this estimate.

The last, major unknown is the position of the lens. York et al. (2005) derived the optical center of the galaxy with an accuracy of $\sim 15 \text{ mas}$ (see Table 1). We seek a center of mass reconstructed to $\sim 1 \text{ mas}$. We first take the position of the lens as inferred from the optical images. Then, as an additional constraint, we use the lens geometry; the lens must be located close to the image axes and to the center of the Einstein ring (Figure 1).

For demonstration purposes, in Figure 1 we display the contours of radio emission observed at 1.687 GHz with a beam FWHM of $50 \times 50 \text{ mas}$. However, this image was available to us only in jpg format downloaded from JVAS 1. We rescaled it by $\sim 5\%$ to align it with well-resolved mirage images at 15 GHz. The image at 1.687 GHz resolves the mirage images of the core and the Einstein ring structures. After rescaling, the center of the ring indicates a plausible position of the lens with an accuracy of $\sim 50 \text{ mas}$. Using all of this information, we find the approximate position of the lens (see Table 1). In the lens model described below, we use Monte Carlo simulations to refine the best lens position within this region.

The VLBA observations at 15 GHz also provide a very precise flux density ratio between mirage images of 3.623 ± 0.065 . However, observations of B2 0218+35 at different frequencies and epochs show a large spread in measured magnification ratios, from 1 to 6 (Biggs et al. 1999; Cohen et al. 2000; Cheung et al. 2014). This large spread in magnification ratio may result from different

propagation effects (Mittal et al. 2007), substructures in the mass distribution (Mao & Schneider 1998; Kochanek & Dalal 2004; Metcalf & Amara 2012; Biggs et al. 2004), or even from microlensing (Vovk & Neronov 2015). To avoid this additional complexity, we do not use the flux ratio as a constraint. However, the best-fit model does yield a magnification ratio that is consistent with the range of values observed at other frequencies

3.2. Lens Modeling

We investigate the properties of the lens system with a MATLAB code inspired by Zitrin et al. (2009, 2013). We construct a $800 \times 800 \text{ mas}$ grid with a resolution of 1 mas. We define coordinates relative to the position of the lens center. We perform all calculations in the image plane because the observed positions of the images are directly linked to the image plane, not to the source plane.

3.2.1. Gravitational Lensing Formalism

We compute the Fermat surface using Eq. (61) from Narayan & Bartelmann (1996):

$$(\vec{\theta} - \vec{\beta}) - \vec{\nabla}_\theta \psi = 0, \quad (1)$$

where $\vec{\theta}$ is the position of a mirage image, $\vec{\beta}$ is the source position, and ψ is the gravitational potential of the lens. The Fermat principle implies that the images form at the extrema (maxima, minima, and saddle points) of the surface (Blandford & Narayan 1986). We then search for the extrema of the Fermat surface using Matlab procedure `extrema2`². Figure 2 shows color contours of the Fermat surface with two minima where the mirage images form. We find the positions of these minima and calculate the offset between their coordinates and positions of the mirage images resolved at 15 GHz.

The position of the images and the gravitational potential of the lens allow us to calculate the time delay between the mirage images. We use Eq (63) from Narayan & Bartelmann (1996):

$$t(\vec{\theta}) = D \frac{(1 + z_L)}{c} \left[\frac{1}{2} (\vec{\theta} - \vec{\beta})^2 - \psi(\vec{\theta}) \right], \quad (2)$$

to calculate the time delay between the arrival of photons from image θ_A and θ_B . We then calculate the difference between the estimated time delay and the time delay measured at 15 GHz.

We calculate magnifications of the mirage images using Eqs (55-60) from Blandford & Narayan (1986). This calculation is also based on the gravitational potential and the positions of the mirage image. We do not, however, use the magnification ratio to extract the lens parameters. We provide the formalism because we do use the magnification later to constrain the origin of the gamma-ray radiation.

3.2.2. Finding a Unique Mass Model

We seek the gravitational potential along with source and lens locations that reproduce the observations. We compare the reconstructed positions of the lensed images with well-resolved mirage images at 15 GHz. As an additional constrain, we use time delay measured at 15 GHz.

¹ <http://www.jb.man.ac.uk/research/gravlens/lensarch/B0218+357/B0218+357.html>

² <http://www.mathworks.com/matlabcentral/fileexchange/12275-extrema-m-extrema2-m>

To find the lens solution, we repeat our calculations of the image positions and the time delay between them for a range of parameters. We investigated a range of complex models for the gravitational potential using the Monte Carlo simulations. We added parameters including a core, a variable slope for the mass distribution, and a variable ellipticity and position angle of the lensing galaxy. None of the added parameter to the lens model where able to improve the fit and reconstruct the observations with desired accuracy. We vary the lens position around the value listed in Table 1. We explore a region of 20 mas with a 1 mas step. We search for the best source position around the value listed in Table 1. **In Appendix A, we describe our Monte Carlo simulations and our investigation of systematic errors associated with lens model.**

We define the best-reconstructed model as the one which reproduces the positions of the mirage images with the smallest offset and where the time delay is within 1σ of the measured time delay at 15 GHz.

3.2.3. The Best Model

We achieved the best reconstruction for an elliptical singular isothermal sphere (Kneib 2014):

$$\psi(r, \theta) = r\theta_E \sqrt{1 - \epsilon \cos(2(\phi - \phi_0))}, \quad (3)$$

where ϵ is an ellipticity of the gravitational potential, ϕ_0 is the position angle of the potential, and θ_E is an Einstein angle defined as:

$$\theta_E = 4\pi \frac{\sigma_0^2}{c^2} \frac{D_{LS}}{D_{OS}}, \quad (4)$$

where σ_0 is the central velocity dispersion of the 3D velocity field, and D_{LS} and D_{OS} are cosmological distances from the lens to the source, and from the observer to the source, respectively. We also define:

$$D \equiv \frac{D_{OL}D_{OS}}{D_{LS}} = hd, \quad (5)$$

where D_{OL} is the distance from the observer to the lens. The parameter h refers to the Hubble constant, $H_0 = h \times 100 \text{ km s}^{-1} \text{ Mpc}^{-1}$. We calculate distances based on a homogenous Friedmann-Lemaître-Robertson-Walker cosmology, using $h = 0.673$, the mean mass density $\Omega_M = 0.315$ and the normalized cosmological constant $\Omega_\Lambda = 0.686$ (Planck Collaboration et al. 2014).

3.2.4. Error Estimation

To estimate statistical errors, we use Monte Carlo chain simulations. We based our algorithm on the MCMC toolbox for `Matlab`³ (Haario et al. 2006).

We test for systematics in our simulations by comparing the numerical solution with an analytic model. The simplest analytic solution is the SIS. We compare the positions of the images, time delays and magnification ratios for the SIS calculated analytically and numerically for positions of the sources across the entire lens plane. The numerical procedure applied on a grid with a 1 mas resolution, on average reconstructs image positions with ~ 0.3 mas. On average, the time delay is reproduced

within 0.01 days, and the magnification ratio within 0.05. This level of precision shows that on a scale of 1 mas, our lens parameters are unaffected by systematic numerical errors.

TABLE 2
RESULTS OF THE FIT

Parameter	Value
Ellipticity ϵ	0.0057 ± 0.0042
Source Position (x_S, y_S)	$(154.2 \pm 0.8, -62.9 \pm 0.7) \text{ mas}$
Lens Position (x_L, y_L)	$(62.2 \pm 0.9, -25.0 \pm 0.8) \text{ mas}$

3.2.5. Lens Modeling Results

Table 1 summarizes the input parameters for the lens model; the ellipticity of the lens, and the source and lens positions. Table 2 shows the model results along with the statistical errors from the Monte Carlo chain simulations.

The fit yields an $\epsilon \sim 0$, essentially an isotropic SIS. We reconstruct the lens and source positions with an accuracy of 1 mas corresponding to 8 pc in the source plane.

The positions of the mirage images are most sensitive to changes of the source position in the tangential direction relative to the images-lens axis. Changing the source position by 1 mas in the tangential direction, moves the mirage images by 5.5 mas. In the radial direction a 1 mas change in the source position displaces the image by only 2.7 mas. Table 3 and Figure 1 show that the model reproduces the observed mirage image positions to 0.4 – 0.8 mas.

TABLE 3
RECONSTRUCTION

Parameter	Value	Difference
Image A	(-0.4, 0)	0.4 mas
Image B	(308.6, -128.0)	0.85 mas
Time Delay	10.7 days	~ 0.2 days
Magnification Ratio	3.85	0.23

3.3. Lens Model and the Jet Alignment

We investigate the origin of variable emission along the relativistic jet. The alignment of the jet and the mass distribution of the lens are necessary to predict the range of time delays and corresponding magnification ratios.

The alignment of the jet of B2 0218+35 is known from the well-resolved radio images which show clear jet-like structures. Wucknitz et al. (2004) show that the jet sub-components are oriented exactly radially with respect to the center of mass of the lens. The existence of the radio Einstein ring implies radial alignment of the jet on scales $\lesssim \text{kpc}$.

We use the alignment of the jet and the lens model (Table 2) to calculate the time delay and corresponding magnification ratio along the jet. Figure 2 shows the result.

The time delay is very sensitive to the distance of the source from the center of the lens. The radial alignment of the jet of B2 0218+35 produces maximal differences

³ <http://helios.fmi.fi/~lainema/mcmc/>

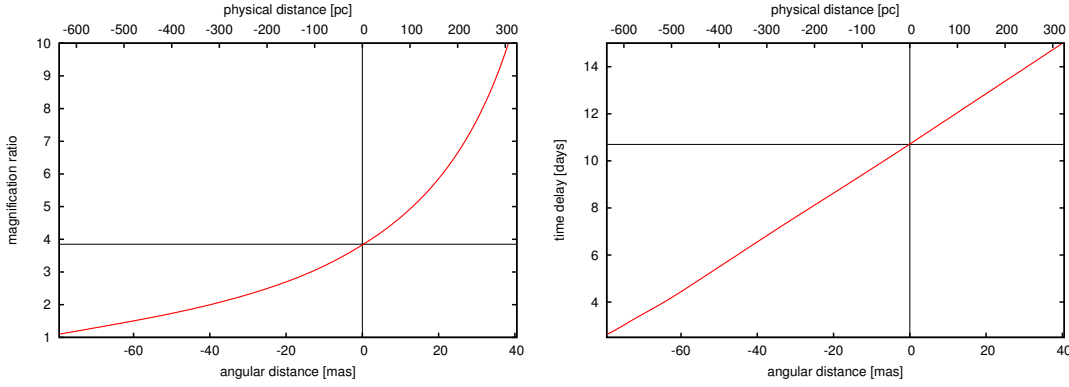


FIG. 2.— Magnification ratios (**Left**) and time delays (**Right**) as a function of the distance between the core and emitting regions along the jet. **Left**: The gray lines indicate the magnification ratio, 3.85, expected at the position of the 15 GHz core. **Right**: The gray lines indicate the time delay of 10.7 days expected for an emitting region coincident with the position of the 15 GHz core.

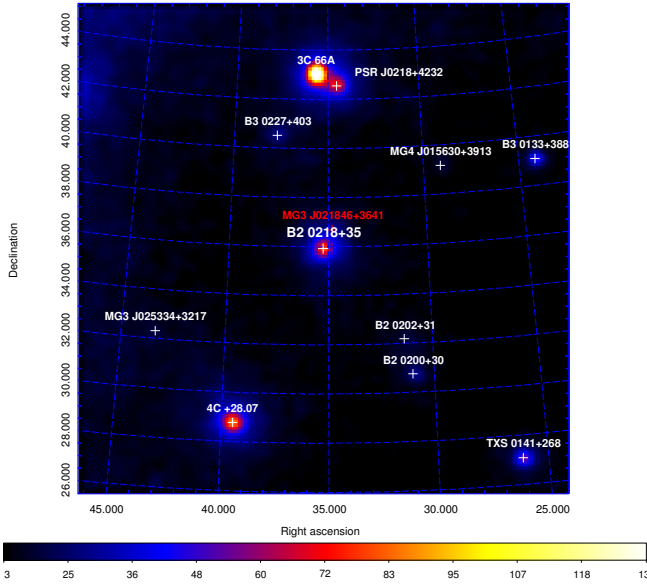


FIG. 3.— *Fermi*-LAT count map of B2 0218+35. The energy range is 100 MeV to 300 GeV.

in the time delay among regions distributed along the jet. In the radial direction the time delay changes by 0.13 days (3.12 hours) per 1 mas but in the tangential direction, it changes much more slowly, 0.01 day per 1 mas.

4. B2 0218+35 AS A GAMMA-RAY SOURCE

B2 0218+35 is a bright gamma-ray source. Here, we analyze the gamma-ray light curve observed with the Large Area Telescope onboard the *Fermi* mission (*Fermi*-LAT, Atwood et al. 2009).

We analyze the *Fermi*-LAT P7REP events and spacecraft data of B2 0218+35 during the period MJD: 54682–57041. We use the standard likelihood tools distributed with the *Science Tools v9r32p5* package available on the *Fermi* Science Support Center webpage.

We only used events in the CLEAN dataset with the highest probability of being photons. We exclude events with zenith angles $> 100^\circ$ to limit contamination by Earth albedo gamma rays produced by cosmic rays interacting with the upper atmosphere. We also remove events with rocking angles $> 52^\circ$ to eliminate time in-

tervals when the Earth entered the LAT Field of View (FoV).

The selected events with reconstructed energies above 100 MeV within a square region of 10° radius are centered on the coordinates of B2 0218+35 (see Figure 3). We analyze the selected photons with a binned maximum likelihood method (Mattox et al. 1996).

We model the background emission using a galactic diffuse emission model (`gll_iem_v05`) with an isotropic component (`iso_clean_v05`; available on the *Fermi* Science Support Center webpage). The fluxes are based on the post-launch instrument response function P7REP_CLEAN_V15.

The XML source model contains all of the sources included in the Second *Fermi*/LAT catalog (Nolan et al. 2012) within a radius of 20° around B2 0218+35. We first analyze the XML source model fitting the sources within 10° ; within an annulus from 10° to 20° we fix the sources to their 2FGL values. We calculate the test statistic (TS) for all the sources located within the 10° radius during the time period MJD: 54682–57041. Sources with a TS lower than 6.5, corresponding to a statistical significance of $\approx 2.5\sigma$, are then fixed in further analysis. The resulting XML source model is then the basis for the 6.5 year light curve in Figure 4. The TS is also based on this source model.

The TS of B2 0218+35 for this dataset is 8890, corresponding to a statistical significance of $\approx 94\sigma$. The energy spectrum is best described by a power law with $\Gamma = 2.28 \pm 0.02$ and an integral flux of $F(0.1 - 300 \text{ GeV}) = (1.42 \pm 0.05) \times 10^{-7} \text{ ph cm}^{-2} \text{ s}^{-1}$. The highest energy event recorded by *Fermi*/LAT corresponds to $\sim 95.7 \text{ GeV}$. The flux in each time bin is reconstructed in the same manner as for the full time range; the photon index and integral flux in these bands are free parameters.

Our goal is to investigate the spatial origin of gamma-ray flares. Thus, we look for periods of flaring activity in the gamma-ray light curve of B2 0218+35. We define a flare as a period of time when the emission in a one-day bin increases by at least two sigma relative to the average flux. Note that Figure 4 shows data in 7-day bins.

Based on our definition, we identify two active periods; a very long flare between MJD: 56160 – 56280, and a short flare consisting of a single bright event, occurring between MJD: 56800 – 57000. Figure 5 shows both

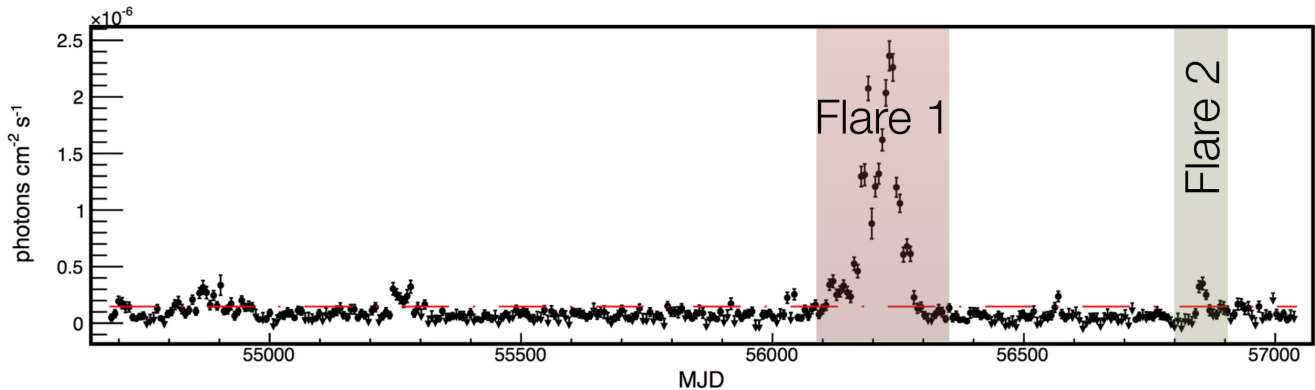


FIG. 4.— *Fermi*-LAT light curve of B2 0218+35 with seven-day binning. The energy range is 100 MeV to 300 GeV.

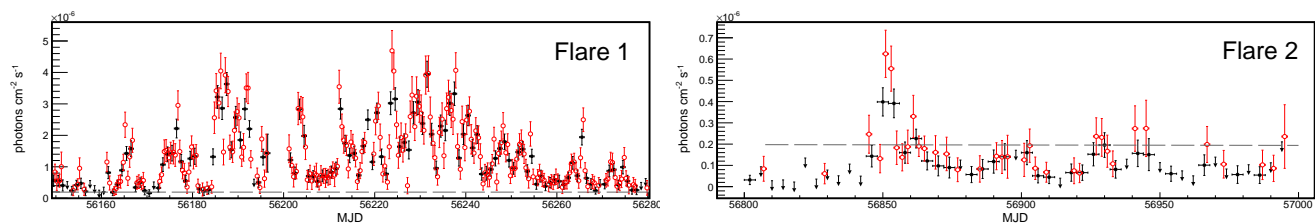


FIG. 5.— *Fermi*-LAT light curves of B2 0218+35 during two flaring periods. The green dashed line represents the average flux ($1.41 \pm 0.04 \times 10^{-7}$ photons cm $^{-2}$ s $^{-1}$) measured from the 6.5 year light curve of B2 0218+35 in the energy range from 100 MeV to 300 GeV. **Top:** Flare 1 with 12-hour binning (black filled circles) and with 6-hour binning (red open circles). **Bottom:** Flare 2 with four-day binning (black filled circles), and two-day binning (red open circles).

flares. Visually it may seem that there are other flares in Figure 4. However, these apparent flares are not significant with one-day bins. We use the light curves for the two significant flares to compute time delays.

5. TIME DELAY MEASUREMENT

In the B2 0218+35 system, radio observations reveal two images separated by ~ 330 mas. The angular resolution of the *Fermi*-LAT detector is ~ 1 deg. Thus the observed gamma-ray light curve is a sum of two unresolved mirage images shifted in time, but with a constant magnification ratio. The temporal resolution of the *Fermi*-LAT detector allows determination of the time delay at gamma ray energies. With sufficiently well-determined time delays, the relationship between the radio and gamma-ray time delays constrain the relative source positions.

The *Fermi*-LAT data cover a long, uninterrupted periods containing the two significant flares. There are several methods for extracting the time delay from these binned data (Barnacka et al. 2015a). We use the standard Autocorrelation Function (ACF), and the more sensitive Double Power Spectrum (DPS) method (Barnacka et al. 2011; Barnacka 2013). The detailed description of the DPS method together with comparison to other methods is described in Barnacka et al. (Section 3.2.2 and Appendix A, 2015a). The DPS is similar to the Cepstrum method (Bogert et al. 1963), where a time series with a delay transforms into Fourier space with the extra component $e^{-2\pi i f a}$, where f is frequency and a is the delay. Squaring the absolute value of this extra component results in a periodic pattern imprinted on the power spectrum. The period of this pattern in the frequency

domain is the inverse of the relative time delay a . We identify the time delay by calculating and analyzing the power spectrum of the power spectrum that includes the periodic pattern. We apply these methods to the first flaring period in Section 5.1.

Monte Carlo simulations demonstrate that this signal processing allows removal of the intrinsic variability of the source. We have previously demonstrated that this procedure yields precise and significant estimates of the time delays (Barnacka et al. 2015a).

The DPS method is very efficient when applied to long, evenly sampled light curves. However, sometimes the flare is an isolated event of very short duration like Flare 2. To treat these flares, we use the Maximum Peak Method (MPM, Section 3.2.3, Barnacka et al. 2015a) where we calculate the ratio between the flux in the flare and flux in the subsequent data. We compare the flux ratios as a function of the lag between the brightest flare and the subsequent light curve with the predictions of the model (Section 5.2) of B2 0218+35.

5.1. Flare 1

Enormous gamma-ray activity occurred during the period MJD: 56160 – 56280. We analyze this time interval using the ACF and DPS (see Figure 6). We obtain a time delay of 11.5 ± 0.5 days for the ACF, and 11.38 ± 0.13 days using the DPS.

To estimate the significance of the detection, we use Monte Carlo simulations following Barnacka et al. (2015a). We produce 10^6 artificial light curves.

The temporal behavior of Flare 1 is not power law noise. The flare consists of a superposition of very short duration flares with large amplitudes. Figure 7 com-

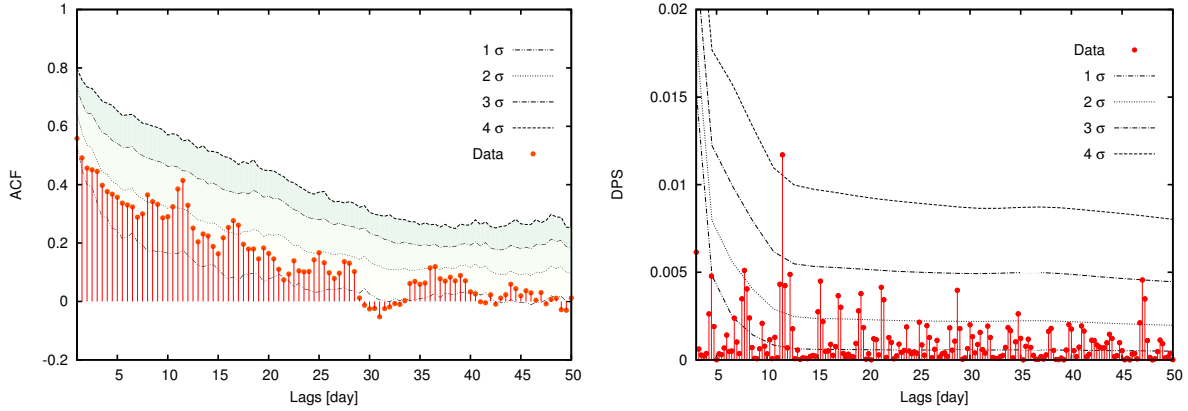


FIG. 6.— Autocorrelation Function (**Left**) and Double Power Spectrum (**Right**) for Flare 1.

compares Flare 1 with the temporal behavior of power law noise with different indices. The temporal behavior during Flare 1 is not well reproduced by any of these pure noise models. Pink noise ($\alpha \sim 1$) is the closest match. The power spectrum of Flare 1 actually returns $\alpha = 0.9$. However, pink noise is not complete description of temporal behavior of Flare 1 because it cannot account for correlated bin-to-bin time variations of large amplitude. Increasing the index of power law noise (e.g. red noise) smooths the large fluctuations and obviously does not reproduce the behavior of the source. Decreasing the index toward white noise increases the fluctuations on bin-to-bin time scales, but the fast rise exponential decay profile that characterizes flares is absent (Peng et al. 2010; Saito et al. 2013). This correlated behavior resulting from the physics of the source is not reproduced by a simple noise model.

Simulations of the signal composed of superpositions of short and bright flares are possible, but the number of parameters required to define the flares is large. Thus following Barnacka et al. (2011), we divide the light curve into overlapping segments. We can use this approach because the flaring activity lasted for almost 200 days and the range of expected time delays is short, < 20 days. We can thus divide the light curve of Flare 1 into three overlapping segments of 128 days each. We apply the ACF and DPS to each of the three segments and then average the results. The error bars are the standard deviation among the three segments in each bin.

Figure 8 (Left) shows the ACF averaged over the segments. We fit the spectrum with an exponential function representing the background and a Lorentzian function representing the signal. The fit returns a time delay of 11.24 ± 0.39 days. However, the error bars are large and the significance of the signal is only 0.3σ .

Figure 8 (Right) shows the DPS from the averaged segments. We fit linear plus Lorentzian profiles to obtain the position of the peak and its significance. The corresponding time delay is 11.33 ± 0.12 days. The signal is 4.13σ above the background. The DPS time delay, detected at high significance, agrees remarkably well with the previously obtained gamma-ray time delay of 11.46 ± 0.16 days reported by Cheung et al. (2014).

The light curve is a superposition of multiple flares. The time between the random flares could mimic a time delay. These “fake” signals should occur only in a frac-

tion of the light curve. A true gravitationally-induced time delay persists over the entire flaring period. The analysis that averages over segments of the light curve distinguishes the real, gravitationally induced, signal from randomly superimposed flares. If there is a real time delay the significance of the time delay increases with averaging over the three periods. For random multiple flares, the significance should not improve. In fact Figure 8 shows that multiple peaks are present because there is a lot of structure in the light curve. However, only the signal in bins around 11.5 days is significant (Figure 8).

5.2. Flare 2

Flare 2, a single, bright flare, occurred in time period MJD: 56800 – 57000. The light curve (2 day bins) around the flare consists mostly of upper limits (Figure 5). This light curve is useless for extracting several-day long time delays. However, the huge advantage of having a single isolated flare is the ease of a direct search for the echo flare. Figure 9 shows the result of application of the Maximum Peak Method (MPM, Section 3.2.3, Barnacka et al. 2015a). The MPM method suggests that the time delay lies in one of two ranges: 9.75 ± 0.5 days or 11 ± 0.25 days. The errors corresponds to the bin width, not the 1σ standard deviation.

6. THE STRUCTURE OF THE GAMMA-RAY SOURCE

So far we have used the radio observations and a lens model to reconstruct the origin of the radio core with a resolution of 1 mas (Section 3.2.5). The Fermi-LAT observations enable precise determination of the time delay for two gamma-ray flares (Section 5). Here, we locate the sources of gamma-ray emission relative to the radio core by combining the radio source map and the Fermi-LAT time delays with the well-measured Hubble constant from Planck Collaboration et al. (2014).

Barnacka et al. (2015b) show that the Hubble parameter implied by the time delay is sensitive to any spatial offset between the emission region that produces the resolved mirage images and the site of the variable emission used to measure time delays. Purely on the basis of the physical processes involved, the gamma-ray emission from B2 0218+35 may not be spatially coincident with the radio core (Barnacka et al. 2014a).

The Hubble parameter, well measured with a variety of independent methods, provides a route to exploring

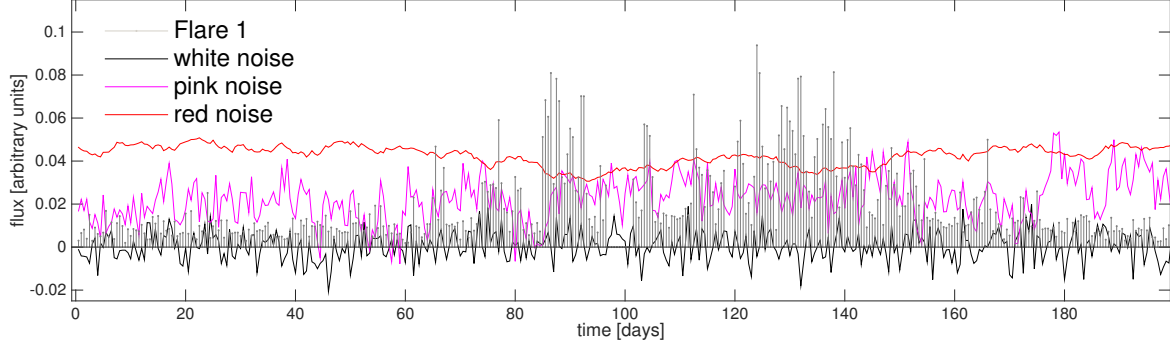


FIG. 7.— Comparison of the temporal behavior of Flare 1 and power law noise: white noise ($\alpha \sim 0$), pink noise ($\alpha \sim 1$), and red noise ($\alpha \sim 2$). We scale the flux of the Flare 1 by a factor of 2×10^4 to align the data with the simulations. The flux of the pink and red noise are shifted by a factor of 0.02 and 0.04, respectively. The shift in scale avoids overlapping of the plots, and facilitates comparison of the temporal structure.

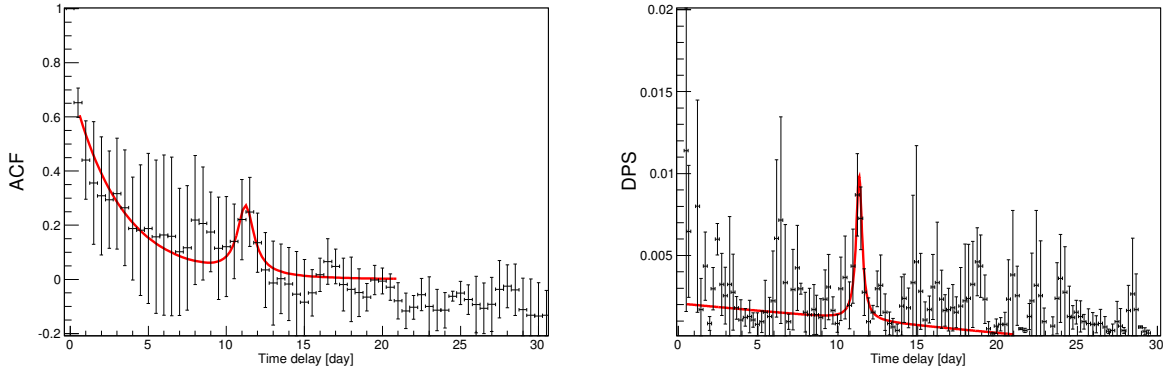


FIG. 8.— Autocorrelation Function (**Left**) and Double Power Spectrum (**Right**) for Flare 1. The spectra are the average of three time sequences. Solid lines are model fits, as described in the text.

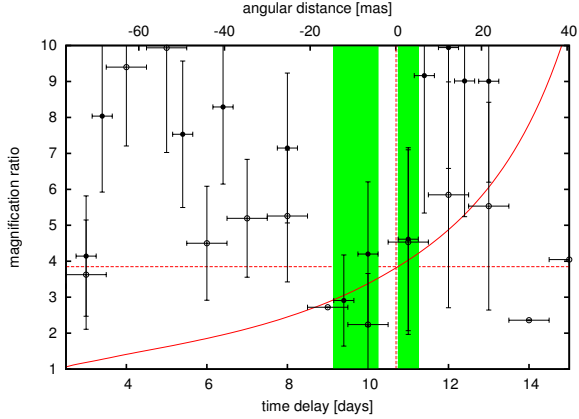


FIG. 9.— The Maximum Peak Method applied to Flare 2. Black and gray points are flux ratios calculated relative to the time bin center at MJD: 56852, using light curve with 0.5 day and 1 day binning, respectively. The solid red line indicates the predicted magnification ratio as a function of the time delay along the jet axis. The red dotted lines indicate the value of the magnification ratio and time delay corresponding to the radio core resolved at 15 GHz. The green area indicates values of time delay where the observed flux ratio is consistent with the model.

this issue. We can use this precisely measured Hubble parameter to evaluate any offset between the radio core and the site of the variable gamma-ray emission. We

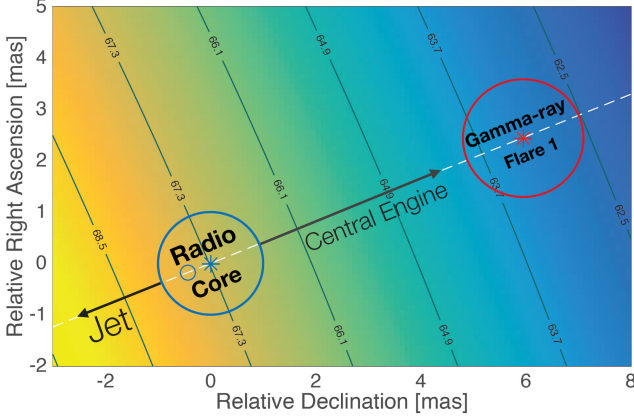
call this method the Hubble Parameter Tuning (HPT) approach.

The Hubble parameter enters into the distance ratio in the time delay calculation (Eq 2). For an SIS gravitational potential, the relation reduces to:

$$h = \frac{d(1 + z_L)(\theta_B^2 - \theta_A^2)}{2c \Delta t}. \quad (6)$$

We have three kinds of constraints on the map of the source from radio to gamma-ray wavelengths: the Hubble parameter, the positions of the lensed images, and the time delay between the images Δt . If there is an offset between the radio core and the gamma-ray emitting regions, the Hubble parameter derived from the Fermi-LAT time delay will differ from the independently measured “true” value. This difference depends on the distance between the radio core and the spatial location of the flare. The offset in Hubble space corresponds to the spatial offset in the source plane (Barnacka et al. 2015b).

To locate the origin of the gamma-ray flares from B2 0218+35, we first fix θ_A and θ_B to the positions of the resolved images of the 15 GHz radio core (Table 1). We use these image positions along with the model of the lens and the cosmological parameters to infer the expected time delay for the position of the 15 GHz radio core. Table 3 lists the reconstructed position; the value



uniquely suited to detailed reconstruction of the source position. The gravitational lensing system is remarkably simple. There are exquisite radio data at several wavelengths along with the extensive Fermi-LAT light curve. These observations combined with the well-constrained Hubble constant enable the first reconstruction of the gamma-ray source positions relative to the radio core and jet.

There are plausible sources of systematics that could in principle account for the offset between the radio core and gamma-ray emission in B2 0218+35. First, we consider a more complex mass distribution for the lens. However, the time delay measured for the resolved radio core (10.5 ± 0.4 days, Biggs et al. 1999) differs from the time delay measured for gamma-ray flares (11.33 ± 0.16 days). This difference clearly indicates that the complexity is in the source, not the lens. Even complex lens models cannot account for multiple time delays. Moreover, we have investigated a range of complex lens model. More complex lens models were unable to reproduce the observations as well as the SIS model.

Although the time delay difference rules out complexity of the lens, the accuracy of radio time delay (0.4 days) allows us to separate the radio core from the gamma-ray flare site only at the $\sim 2\sigma$ level. The time delay can be translated into a relative position in the source plane. The accuracy of 0.4 days corresponds to ~ 3 mas. We use the position of the radio images reconstructed with 1 mas resolution to measure the distance between the emission sites (51.2 ± 8.8 pc), and we obtain a separation significant at the $\sim 3\sigma$ level.

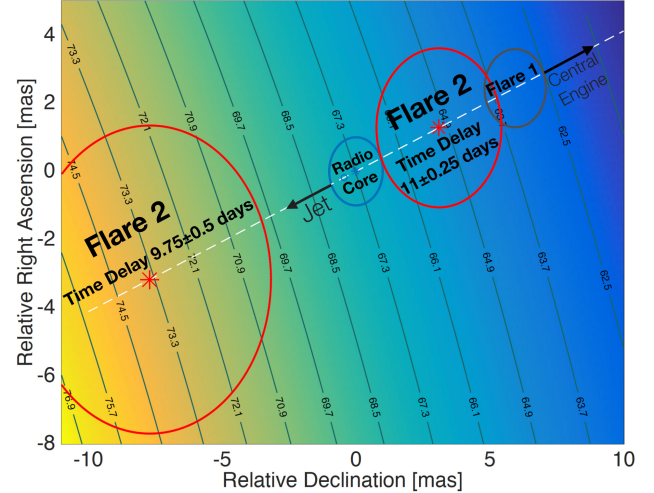
We next consider systematics of the Hubble constant measurement. To measure the offset we use a Hubble parameter, $H_0 = 67.3 \pm 1.2 \text{ km s}^{-1} \text{ Mpc}^{-1}$, obtained by Planck Collaboration et al. (2014). Many independent methods provide a measure of H_0 . For example the Hubble Space Telescope Key Project provides $H_0 = 72 \pm 8 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (Freedman et al. 2001), the Cepheid distance ladder gives $73.8 \pm 2.4 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (Riess et al. 2011a,b) and 74.3 ± 1.5 (stat) ± 2.1 (sys) $\text{km s}^{-1} \text{ Mpc}^{-1}$ (Freedman et al. 2012).

The gamma-ray time delay combined with the position of the radio core gives a Hubble parameter of $H_0 = 63.64 \pm 0.67 \text{ km s}^{-1} \text{ Mpc}^{-1}$. Thus, even if we use the largest value (74.3 ± 1.5 (stat) ± 2.1 (sys) $\text{km s}^{-1} \text{ Mpc}^{-1}$) we obtain a significant offset between the radio core and the gamma ray of at least $\sim 3\sigma$. Therefore, the separation between the radio core and the gamma-ray emission is robust to the large spread in values of the Hubble constant.

Application of the method to other sources may not be as straightforward. For example, fewer constraints like well-resolved images together with time delays at the same frequency. Light curves may not be as well sampled as at gamma rays. The radio data might be insufficient to reconstruct the projection of the jet. Furthermore, observations of relatively nearby sources show that jets can be bent, thus introducing additional uncertainty in measuring distances between emitting regions.

7.1. Comparison with PKS1830-211

PKS 1830-211 is the only other gravitationally lensed gamma-ray blazar known currently. Analysis of the



100 pc. Radio telescopes probe synchrotron radiation produced in optically thick parts of the jet. The radio core is often interpreted as the location where the jet opacity to synchrotron self-absorption is 1 (Blandford & Königl 1979). Observationally, the radio core is the region of peak intensity generated by a compact component at the apparently upstream end of the jet (Marscher 2008; Haga et al. 2015).

Measurement of the distance between a radio core and the central engine is difficult. These measurements have only been possible for nearby sources with prominent two-sided jets. Observing outflows in two opposite directions then constrains the position of the central engine (Haga et al. 2015).

For gamma-ray blazars the two-sided jet is presumably present, but the counterjet is too faint for detection because of relativistic beaming. Thus, in blazars, we observe only one sided-jets. As summarized by Haga et al. (2015), the general picture is that a central engine exists somewhere upstream of observed cores. B2 0218+35 provides the first direct observational constraint.

In B2 0218+35 the bright gamma-ray flare occurred upstream in the jet at the projected distance of 51.2 ± 8.8 pc from the 15 GHz radio core. Thus the central engine must be at least this far away from the radio core. The Hubble tuning approach we use can enable measurement of the apparent velocities of gamma-ray emitting knots. Based on this measurement, we can predict the time of a plausible interaction with the radio core. For B2 0218+35 we predict increased emission at gamma ray and/or radio wavelengths within a year of July 2016.

7.3. Gravitational Lensing and X-ray Sources

The improvement of angular resolution at X-ray wavelengths with *Chandra* enabled the discovery of high energy extragalactic jets extending over hundreds of kiloparsecs (Schwartz et al. 2000; Chartas et al. 2000; Siemiginowska et al. 2002; Sambruna et al. 2002, 2004; Marshall et al. 2005; Sambruna et al. 2006; Harris & Krawczynski 2006; Tavecchio et al. 2007). In fact, our investigations of the structure of lensed gamma-ray sources were inspired by *Chandra*'s discovery of flaring emission from HST-1, a knot of strong X-ray emission displaced from the core in the nearby galaxy M87 (Harris et al. 2006). Recently, deep *Chandra* observations of Pictor A revealed the high-energy flares located in knots displaced along the jet (Hardcastle et al. 2015).

For sources at redshift ~ 1 , the *Chandra* resolution of 0.5 arcseconds corresponds to 4 kpc. Thus, knots like HST-1 cannot be resolved. Improvement in angular resolution of at least two orders of magnitude is needed to resolve these sources and to explore their evolution.

There are, however, ~ 20 gravitationally lensed quasars with associated X-ray emission. The sources have been monitored in searches for microlensing (Chartas et al. 2002; Dai et al. 2003; Chartas et al. 2012; Chen et al. 2012; Mosquera et al. 2013). These data and future monitoring of variable X-ray sources may enable measurement of time delays.

These sources have been also monitored at radio and optical wavelengths. Combining these observations along the lines we have followed for B2 0218+35 may enable reconstruction of these sources based on lensing models. If displacements of the X-ray emitting regions along the

jets are common, they pose challenges to understanding of the particle acceleration mechanism. They may also increase our understanding of the distribution of Hubble constants derived from time delays (Barnacka et al. 2015b).

7.4. Gravitational Lensing and SKA

SKA will observe thousands of gravitationally lensed quasars with a resolution of ~ 2 mas at 10 GHz, and ~ 20 mas at 1 GHz (Dewdney et al. 2009; Godfrey et al. 2012; McKean et al. 2015). These radio observations will provide a foundation for reconstructing the mass distribution of lenses and the positions of radio cores.

All radio quasars have X-ray emission (Risaliti & Lusso 2015). Thus, among these lensed systems, there will be a large population of quasars with variable high energy emission where time delays can be measured.

An ensemble of high-energy quasars with measured time delays and reconstructed source structure based on robust lensing models will enable investigation of the origin of X-ray radiation and the connection between the radio and high-energy emission. The large redshift range of lensed quasars should provide constraints on the co-evolution of radio and high-energy jets.

8. CONCLUSIONS

B2 0218+35 is one of only two known gravitationally lensed systems detected at gamma rays. We reconstruct the mass distribution of its lensing galaxy and the properties of the jet based on well-resolved radio observations. We use the dense Fermi-LAT light curves to measure time delays for two gamma-ray flares. The position of the mirage images, the time delay, and the independently known Hubble constant enable measurement of the spatial offset between the gamma-ray emission region and the radio core.

Our reconstruction of the lensed source shows that the extended flare (Flare 1) is displaced from the radio core at the $\sim 3\sigma$ level. The displacement is upstream from the jet providing the first direct observational constraint on the location of the central engine relative to the radio core for blazars.

A shorter flare (Flare 2) may be an event following Flare 1. If Flare 1 and Flare 2 are indeed connected then the knot which produced these gamma-ray flares moves at apparent velocity of $\sim 70c$. Thus the model makes a testable prediction. There should be an interaction with the radio core within a year of July 2016.

The only other known gravitationally lensed gamma-ray blazar is PKS 1830-211. This source also has complex structure with gamma-ray flares originating from multiple regions along the jet (Barnacka et al. 2011, 2015a).

Lensed high-energy sources monitored with detectors like *Chandra*, Swift and NuSTAR offer rich opportunities to extend this powerful lens modeling approach to other sources. There are more than 20 known lensed quasars with associated X-ray emission. Some of these systems already have enough observations to reconstruct the mass distribution of the lens. Further monitoring will enable measurement of time delays with X-ray detectors.

In the near future, SKA will resolve thousands of radio images of gravitationally lensed quasars. Many of these quasars will also have prominent variable X-ray emission,

allowing recovery of time delays. This ensemble of observations combined with the power of strong gravitational lensing will probe the origin of X-ray radiation, its connection to radio emission, and the cosmic evolution of jets at radio and high energies.

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APPENDIX

MONTE CARLO SIMULATIONS AND LENS MODELING

Selecting the class of models is a key part of lens modeling. A simple and useful mass model of a galaxy acting as a lens is an isothermal model with density $\rho \propto r^{-2}$ and a flat rotation curve. Moreover, the isothermal profile is consistent with a large range of observations of spiral and elliptical galaxies (Fabbiano 1989; Maoz & Rix 1993; Kochanek 1995; Rix et al. 1997; Cohn et al. 2001; Treu & Koopmans 2002; Koopmans & Treu 2003).

Here, our goal is to find a unique mass distribution for the lens. Therefore, we investigate a lens profile allowing for a more complex mass distribution. We use a softened power law potential (Keeton 2001, Eq. 25):

$$\phi = b(s^2 + x^2 + y^2/q^2)^{\alpha/2} - b s^{\alpha}, \quad (\text{A1})$$

where b is the Einstein radius, s is a scale radius of a flat core (in mas), q is the projected axis ratio, and α is a power law exponent. The softened power law potential with $s = 0$, $q = 1$, and $\alpha = 1$ reduces to the SIS potential.

Table 4 shows the range of parameters we explore using Monte Carlo simulations. These range of parameters are constrained based on the set of radio and optical observations described in Section 3.1.

TABLE 4
RANGE OF PARAMETERS FOR THE MONTE CARLO SIMULATIONS

Parameter	Min	Max
s [mas]	0	50
q	0.9	1
α	0.96	1.04
x_S	350	370
y_S	332.5	352.5
x_L	248	288
y_L	284.6	324.6

We use Monte Carlo simulations to explore lens models defined by Eq. (A1) varying in the range of parameters listed in Table 4. We use the MCMC⁴ toolbox within MATLAB. This toolbox generates and analyzes Metropolis-Hastings MCMC chains using a multivariate Gaussian proposal distribution. Table 5 and Figures 12 and 13 shows the results of the MC simulations. The derived parameters are very close to the ideal SIS where $s = 0$, $q = 1$, and $\alpha = 1$.

TABLE 5
RESULTS OF THE MONTE CARLO SIMULATIONS.

Parameter	mean ^a	std ^b	MCerr ^c	τ ^d	geweke ^e
s	6.5639	4.5181	0.1014	28.90	0.971
q	0.9925	0.0055	0.0001	25.19	0.999
α	1.0005	0.0020	5.08e-05	29.60	0.999
x_S	360.06	0.8658	0.0205	29.63	0.999
y_S	342.44	0.7878	0.0174	29.18	0.999
x_L	267.98	0.9659	0.0203	23.79	0.999
y_L	304.69	0.8072	0.0178	27.11	0.999

^aThe mean values estimated from the chain of 5×10^5 simulations

^bThe standard deviations

^cAn estimate of the Monte Carlo error

^dThe integrated autocorrelation time

^eA simple test for a null hypothesis that the chain has converged

The Monte Carlo simulations show that the best global solution for the lens model for B2 0218+35 is the SIS. To exclude other solutions, we have run an additional 10^6 MC simulation uniformly sampled over the range of parameters from Table 4. We identified local minima with parameters for the lens potential that reproduce the position of the images. All models that reconstruct the image within at least 5 mas are very close the SIS. Moreover, all models with

⁴ <http://helios.fmi.fi/~lainema/mcmc/>

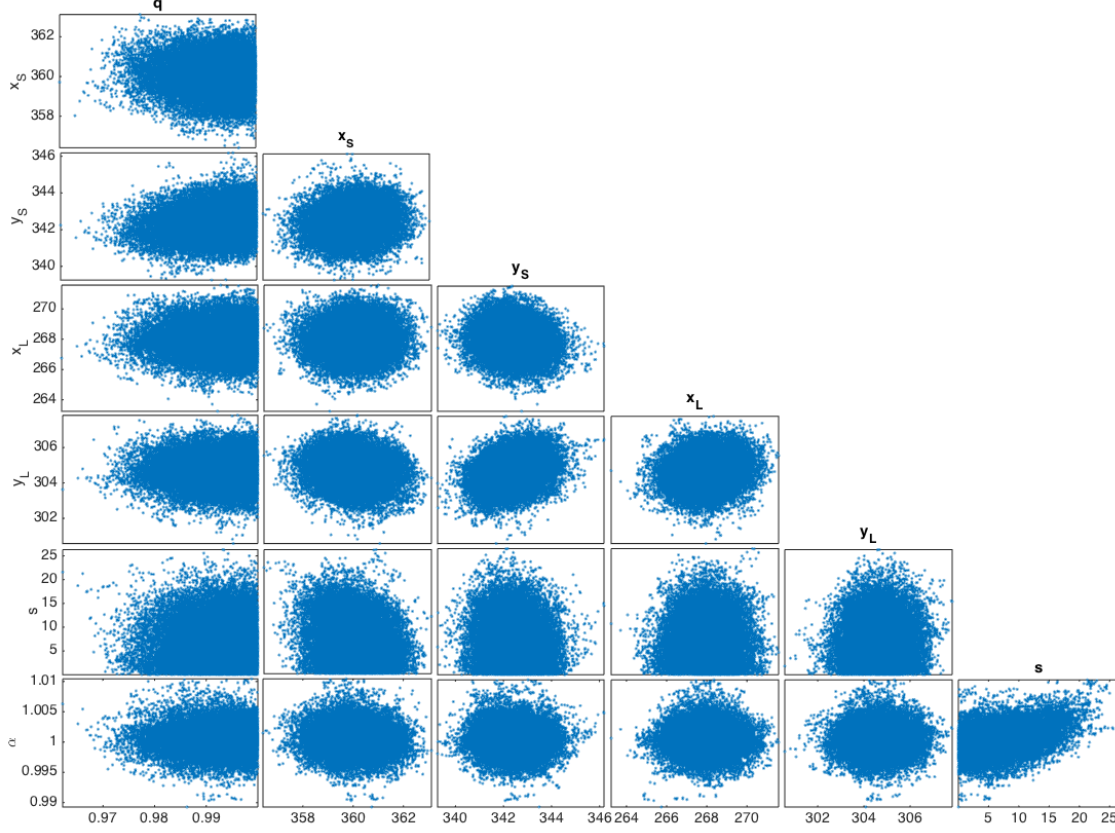


FIG. 12.— Pairwise scatterplots showing the bivariate marginal distributions for a softened power law potential simulated using the Metropolis-Hastings chains.

a more complex gravitational potential that provide a reasonable reconstruction of the mirage images fail to reproduce the radio time delay.

Precise reconstruction of the distance between the emitting regions of the well resolved mirage images, and the emitting region with the well measured time delay rely on knowledge of the mass distribution of the lens. Different lens models result in different rates of change of the time delay as a function of the position of the source. In principle, this rate is the source of systematics in calibrating the distance between the emitting regions.

We calculate the rates of change in the time delay around the source position for different parameters of the lens model. We calculate the change in the time delay for source positions moved by 6 mas in the radial direction. We calculate the expected change in the time delay for models deviating from the SIS. We use the error in the lens parameters estimated from the Monte Carlo simulations (Table 5). We investigate lens models with parameters α , s , and q within 1σ and 3σ from the SIS.

TABLE 6

Parameter within 1σ	$d\Delta t/dr$	$dRatio/dr$	Dist [mas]	Parameter within 3σ	$d\Delta t/dr$	$dRatio/dr$	Dist [mas]
SIS	0.61 days/6 mas	0.55/6 mas	1.25	SIS	0.61 days/6 mas	0.55/6 mas	
$\alpha = 0.998$	0.613 days/6 mas	0.47/6 mas	4.5	$\alpha = 0.994$	0.62 days/6 mas	0.48/6 mas	12
$\alpha = 1.002$	0.61 days/6 mas	0.5/6 mas	4.6	$\alpha = 1.006$	0.6 days/6 mas	0.48/6 mas	12
$s = 4.5$	0.61 days/6 mas	0.55/6 mas	1.8	$s = 13.5$	0.61 days/6 mas	0.55/6 mas	1.8
$q = 1.0055$	0.58 days/6 mas	0.5/6 mas	2.6	$q = 1.0165$	0.7 days/6 mas	0.43/6 mas	4.6

Table 6 shows the expected differences in time delays and magnification ratios. We also list the resulting difference between the reconstructed position of the images and positions of the observed images. For example, even a change as small as 0.002 in the α parameter results in a significant change in the reconstructed image positions. The calculations summarized in Table 6 demonstrate that the estimated offset between the radio core and region of the gamma-ray flare of 6.6 ± 1.1 mas does not suffer from systematics in the lens modeling. The offset is estimated with $\sim 20\%$ accuracy.

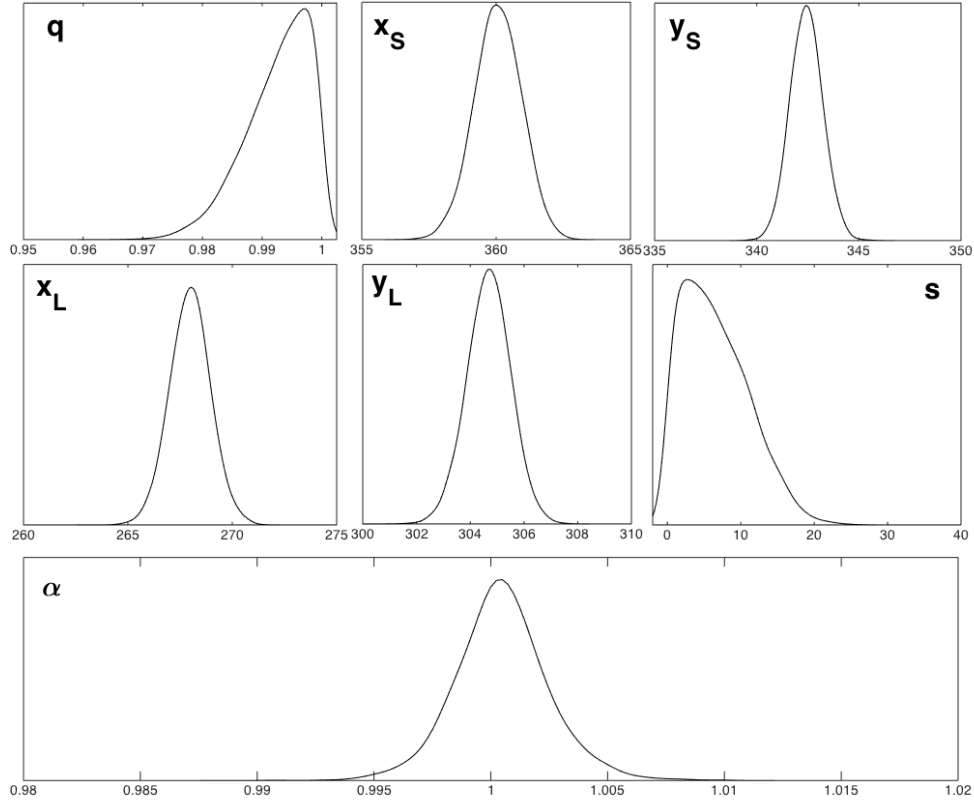


FIG. 13.— The univariate marginalized probabilities for all parameters of the softened power law potential.

As demonstrated in Table 6, the lens model cannot introduce uncertainties of more than 5%. Therefore, our estimation of the offset between the radio core and gamma-ray flare is robust.

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